David B. Fossan

1934-2003

Nuclear Chirality

Basic symmetries in nuclear structure

Rotational and space inversion invariance:

- *result from the isotropy of space,*
- *as a consequence spin and parity are good quantum numbers for nuclear states.*

Time reversal invariance:

- *result from the reversibility of motion in time.*

Notation:

$R(\omega)$ –rotation,

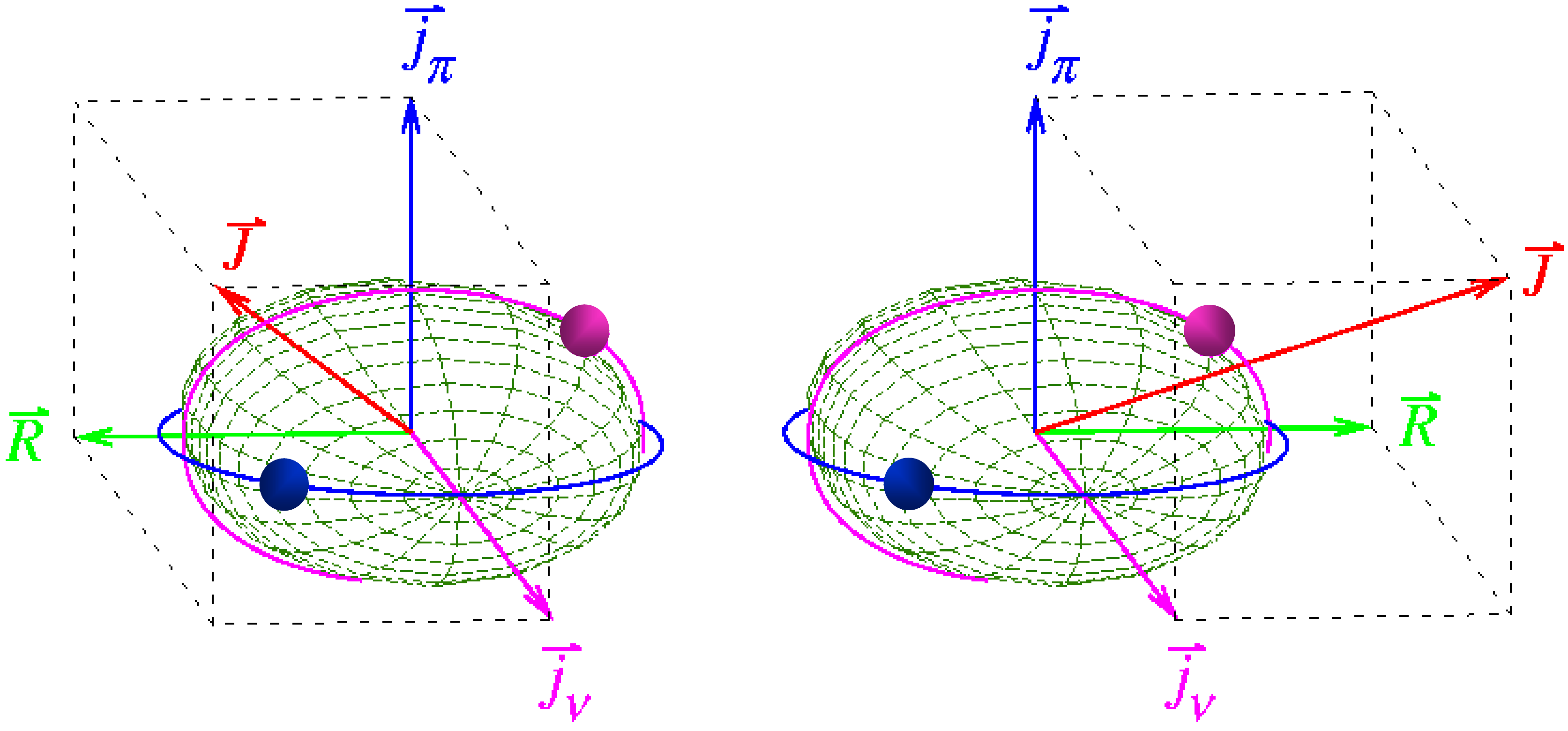
$\mathbf{P}$ –space inversion,

$\mathbf{T}$ –time reversal.

Spontaneous symmetry breaking or nuclear Jahn-Teller effect

The violation of any symmetry in the intrinsic reference frame has a profound influence on the structure of the wavefunction in the laboratory reference frame and therefore is manifest as a distinct feature in excitation modes.

Single-particle configurations in triaxial nuclei may result in three perpendicular angular momenta.



Space inversion vs time reversal:

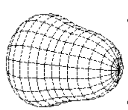
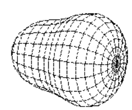
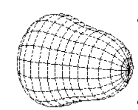
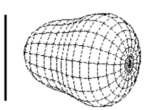
Space inversion operation represented by $\mathbf{P}$ *is linear:*

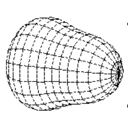
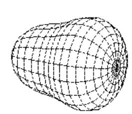
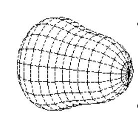
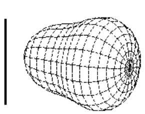
$$\mathbf{P}\,(a|\psi_1\rangle + b|\psi_2\rangle) = a\,\mathbf{P}\,|\psi_1\rangle + b\,\mathbf{P}\,|\psi_2\rangle.$$

For the unitary operator $\mathbf{P}$ *:*

$$\mathbf{P}^2 = 1, \quad \mathbf{P}^{-1} = \mathbf{P} = \mathbf{P}^\dagger.$$

Eigenstates of $\mathbf{P}$ *with eigenvalues* $\pi=\pm1$ *can be formed:*

$\mathbf{P}\,1/\sqrt{2}\,($ $|$  $\rangle + |$  $\rangle$ $) = 1/\sqrt{2}\,($ $|$  $\rangle + |$  $\rangle$ $),$

$\mathbf{P}\,1/\sqrt{2}\,($ $|$  $\rangle - |$  $\rangle$ $) = -1/\sqrt{2}\,($ $|$  $\rangle - |$  $\rangle$ $).$

If $[\,\mathbf{P}\,,\,\mathbf{H}\,]=0,$ *parity is a good quantum number for nuclear states.*

Space inversion vs time reversal:

Time reversal operation represented by $\mathbf{T}$ *is antilinear:*

$$\mathbf{T}(\mathbf{a}|\psi_1\rangle+\mathbf{b}|\psi_2\rangle)=\mathbf{a}^*\,\mathbf{T}\,|\psi_1\rangle+\mathbf{b}^*\,\mathbf{T}|\psi_2\rangle.$$

For the antiunitary operator $\mathbf{T}$ *:*

$\mathbf{T}^2 = (-1)^{2I} = (-1)^A$, $\mathbf{I}$*- spin,* $\mathbf{A}$*- number of fermions.*

Eigenstates of $\mathbf{T}$ *<u>can not</u> be defined.*

For the nuclear hamiltonian which is invariant under time reversal the wave functions for physical states are required to be invariant under the operator $O = T\,R_y(\pi)$.

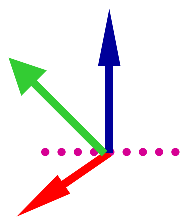
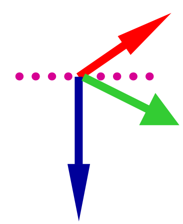
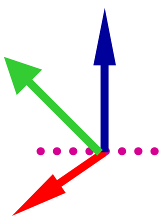
T *denotes time reversal .*

$R_y(\pi)$ *denotes rotation by 180º around the axis perpendicular to the quantization axis.*

With these definitions the O *operator is a complex conjugation of expansion coefficients for wave functions in* $|IM\rangle$ *basis.*

For the planar states of three angular momenta:

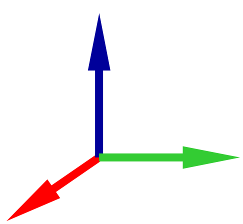
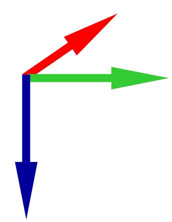
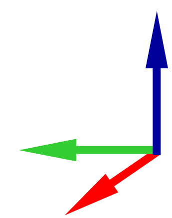
$$O\,|I\,P\rangle = T\,R_y(\pi)\,|I\,P\rangle = |I\,P\rangle\,.$$

$T\,R_y(\pi)\,\Big|$  $\Big\rangle = T\,\Big|$  $\Big\rangle = \Big|$  $\Big\rangle$

For the right- and left-handed states of three mutually orthogonal angular momenta:

$$O\,|I\,R\rangle = T\,R_y(\pi)\,|I\,R\rangle = |I\,L\rangle\,,$$

$$O\,|I\,L\rangle = T\,R_y(\pi)\,|I\,L\rangle = |I\,R\rangle\,.$$

$T\,R_y(\pi)\Big|$  $\Big\rangle = T\Big|$  $\Big\rangle = \Big|$  $\Big\rangle$

For $|I\,R\rangle$ and $|I\,L\rangle$ quantum mechanical analysis for a two level system directly applies.

(See for example ***Feynman lectures on Physics.****)*

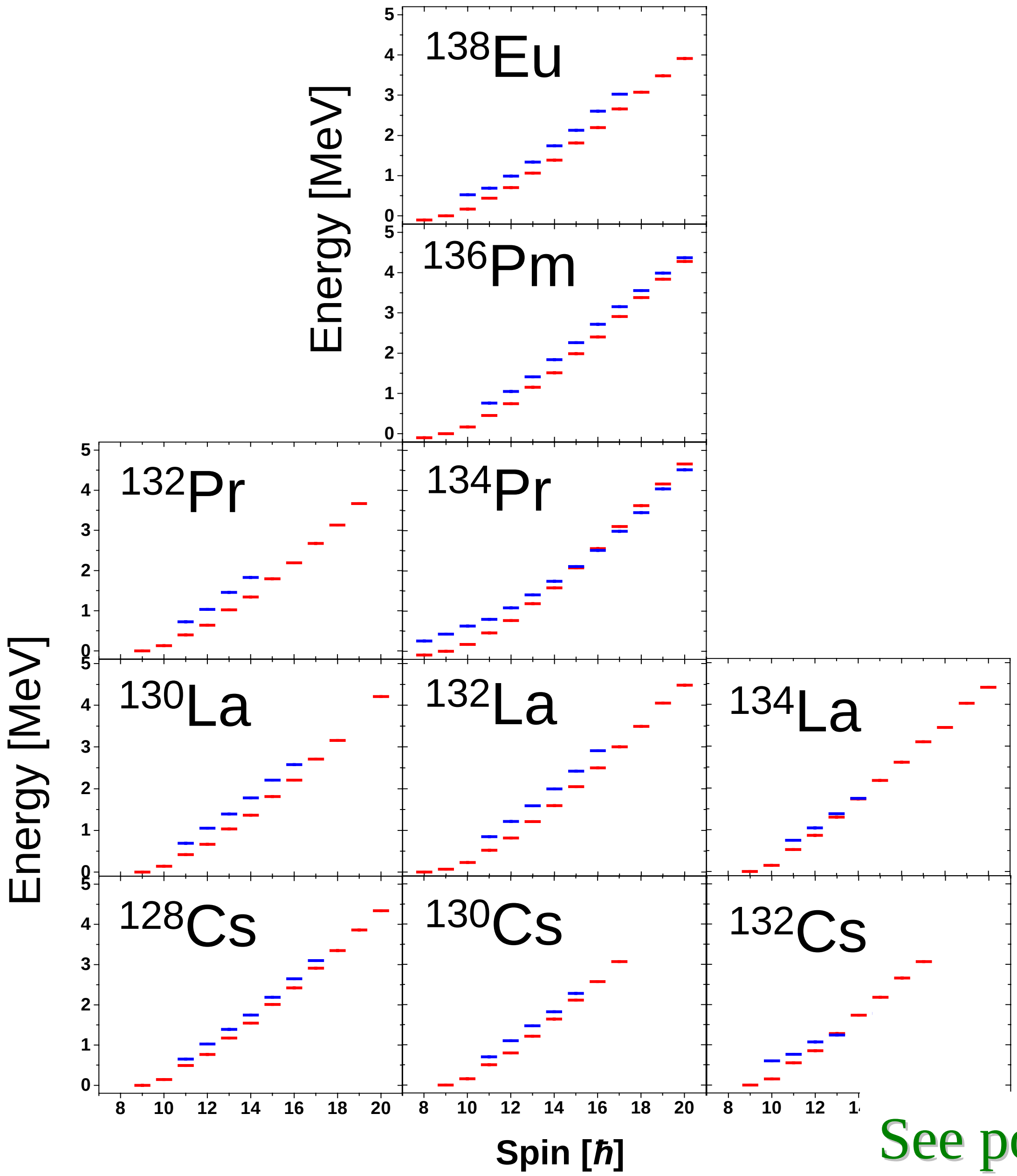
Physical states invariant under O are:

$$\left|I\ +\right\rangle = \frac{1}{\sqrt{2}}\left(\left|IR\right\rangle + \left|IL\right\rangle\right),$$

$$\left|I\ -\right\rangle = \frac{i}{\sqrt{2}}\left(\left|IR\right\rangle - \left|IL\right\rangle\right),$$

Experimental evidence for doublet bands:

Systematics of partner bands in odd-odd A~130 nuclei.

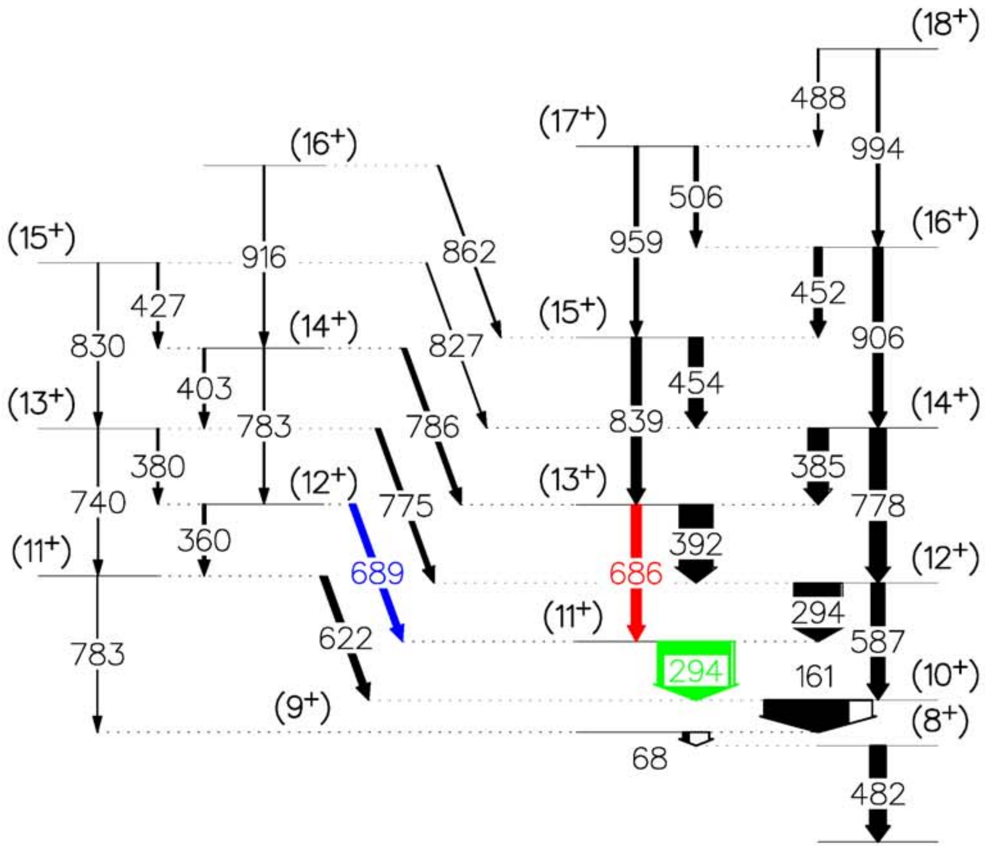


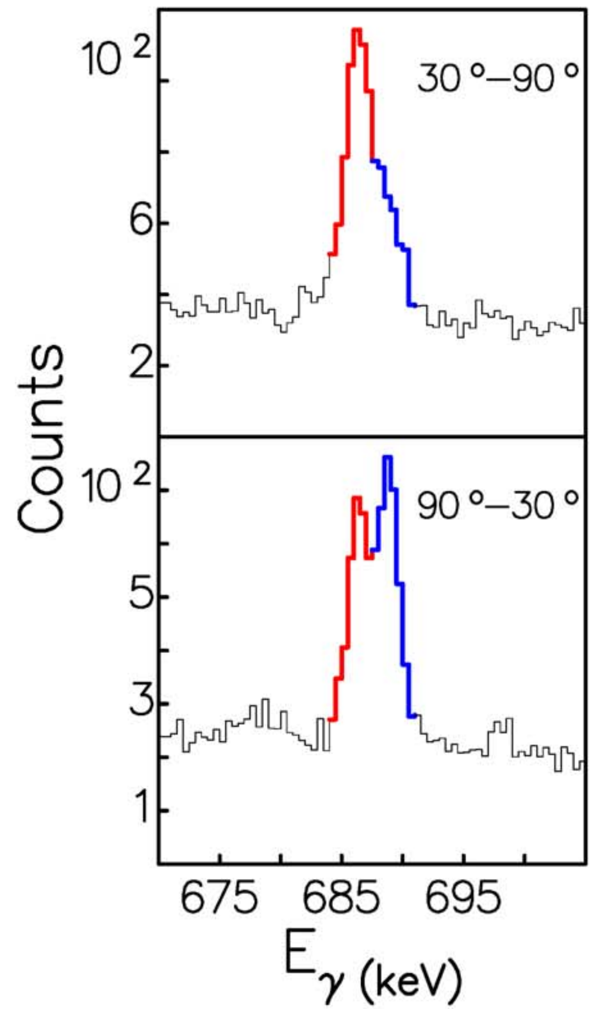
See poster of A. Hecht

Angular correlation (DCO) measurement for ^{132}La.

$$R_{DCO}(294\ keV\ M1/E2\text{-}686\ keV\ E2) = 0.46(6)$$

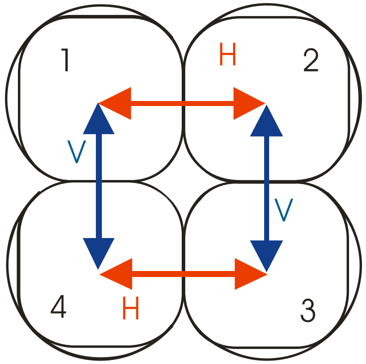
$$R_{DCO}(294\ keV\ M1/E2\text{-}689\ keV\ ?) = 1.4(2)$$





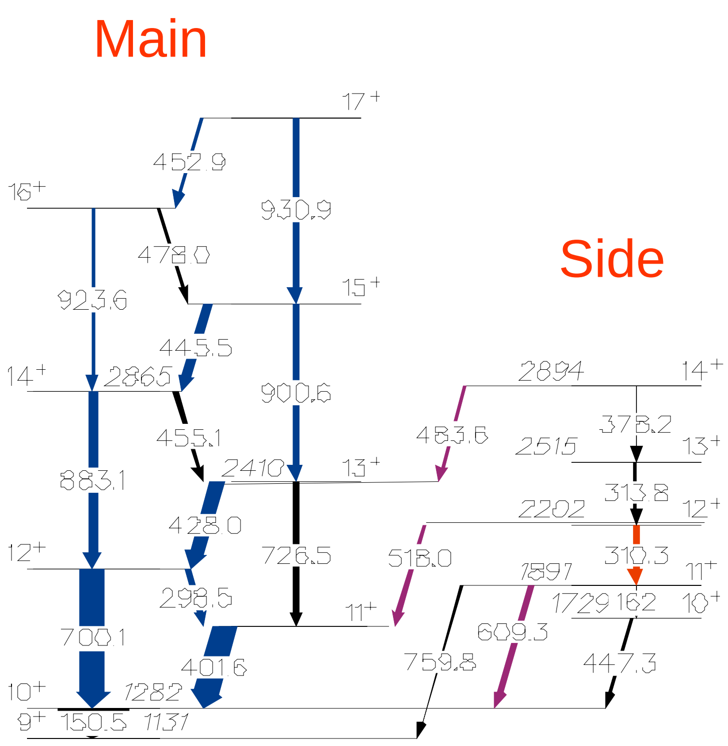
Polarization measurements in ^{132}Cs

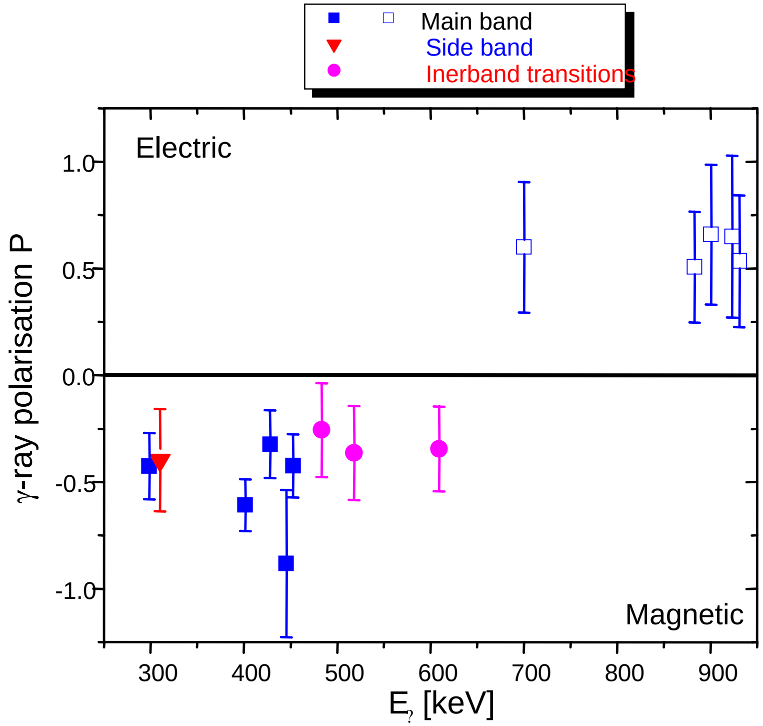
[G Rainovski et al., PRC 68, (2003) 024318].



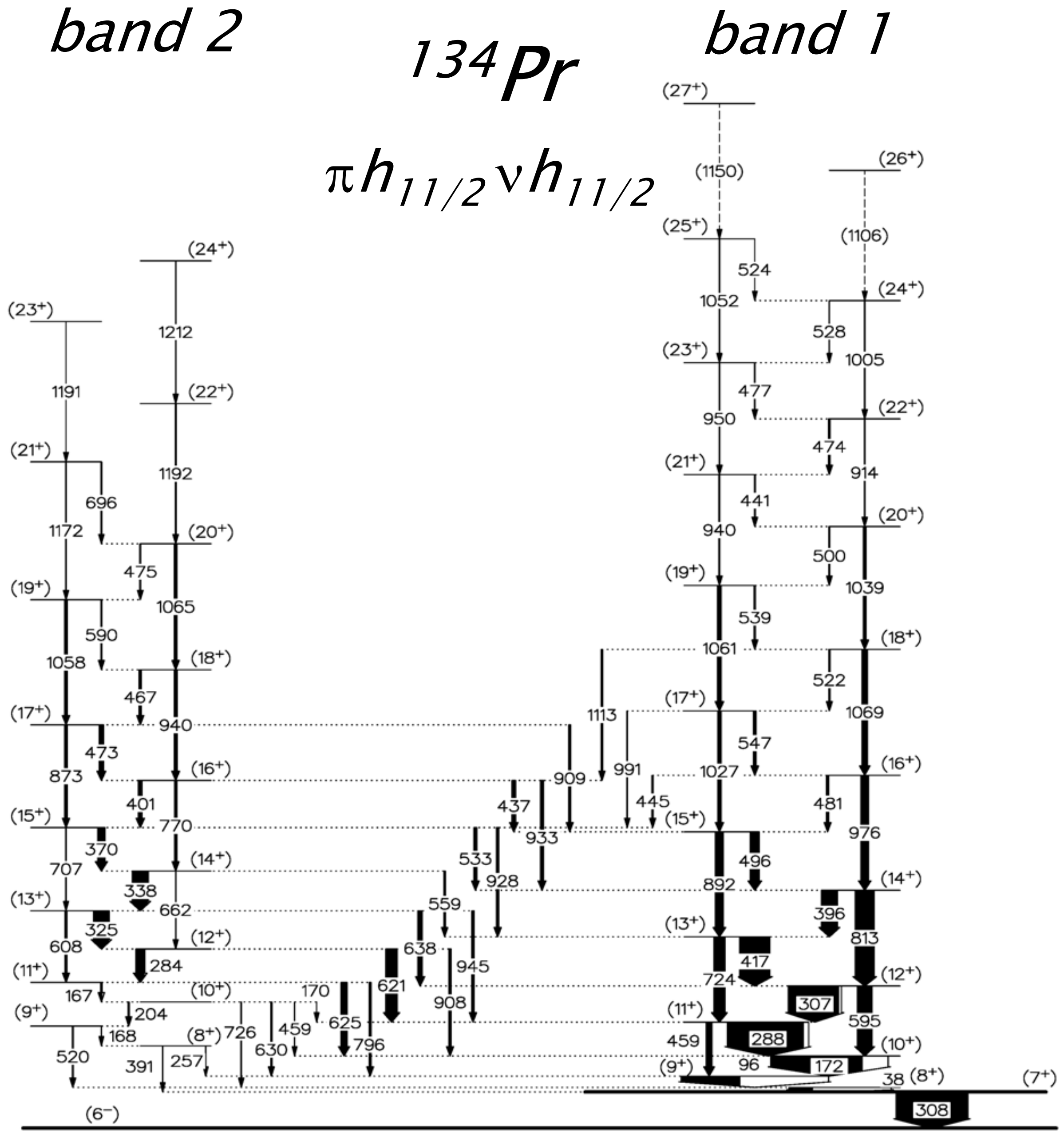
$$P = \frac{1}{Q(E_\gamma)} \frac{N_v - N_h}{N_v + N_h}$$

$Q(E_\gamma)$ – P.M. Jones *et al.*, NIM A 362 (1995) 556





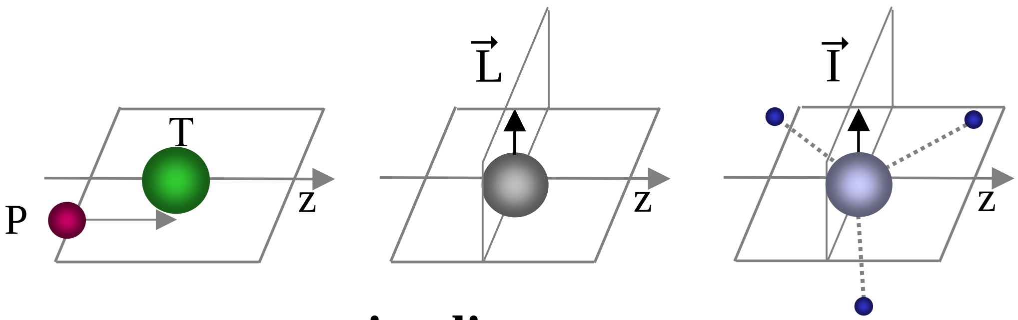
Results of the Gammasphere GS2K009 experiment.



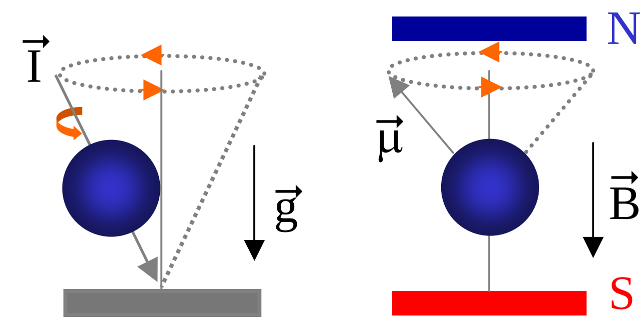
The unique parity argument gives model independent configuration assignment for partner bands !

- *electromagnetic operators are one-body operators;*
- *matrix elements for M1 and E2 operators are non-zero between single particle orbitals with the same parity only;*
- *in odd-odd nuclei M1 and E2 transitions are strongly hindered between configurations involving unique- and normal-parity valence single particle orbitals, despite of the same resulting parity for observed bands;*
- *the main bands are known to be built on unique-parity orbitals;*
- *the observation of M1/E2 links yields the same configuration for the side bands as for the main bands, since no other unique parity orbitals are near the Fermi level.*

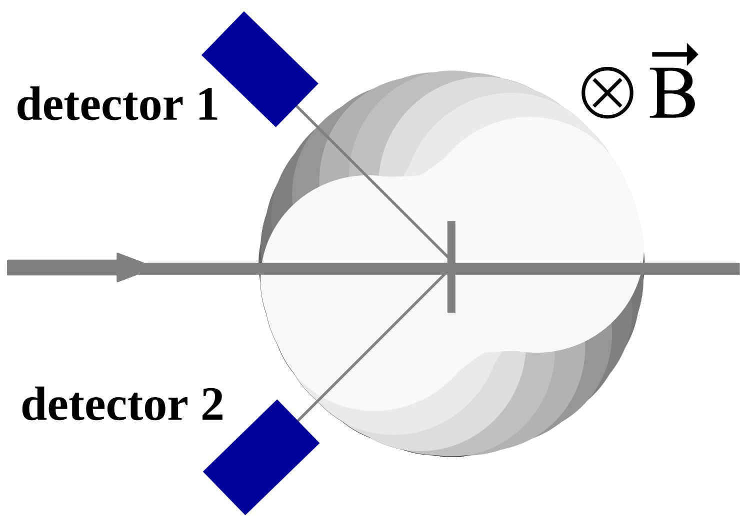
Unique parity configuration assignments for the main band from magnetic moment measurements.



spin alignment

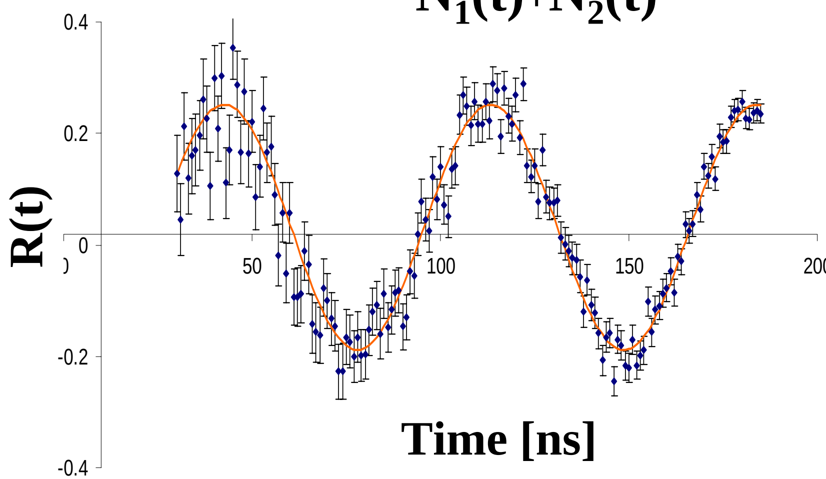


Larmor precession



precession of γ-ray angular distribution

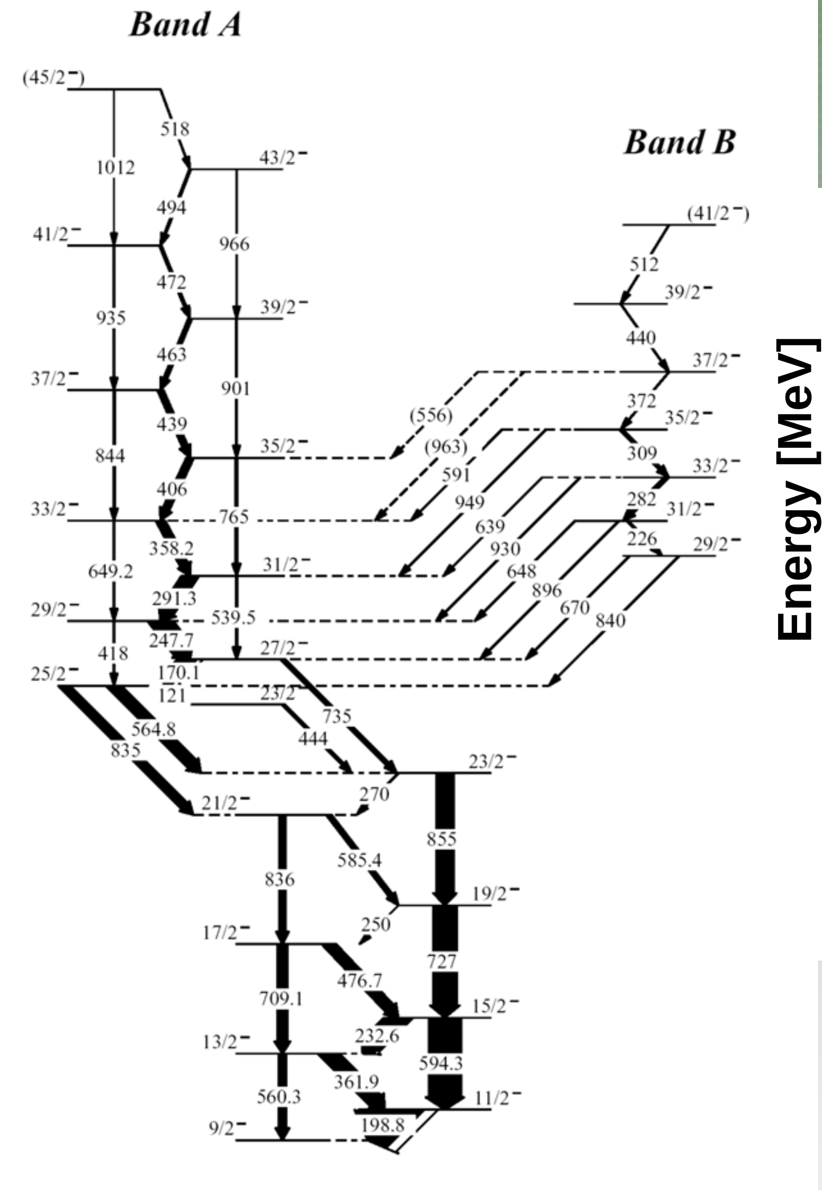
^{128}Cs $\mathbf{R(t)} = \dfrac{\mathbf{N_1(t)-N_2(t)}}{\mathbf{N_1(t)+N_2(t)}}$

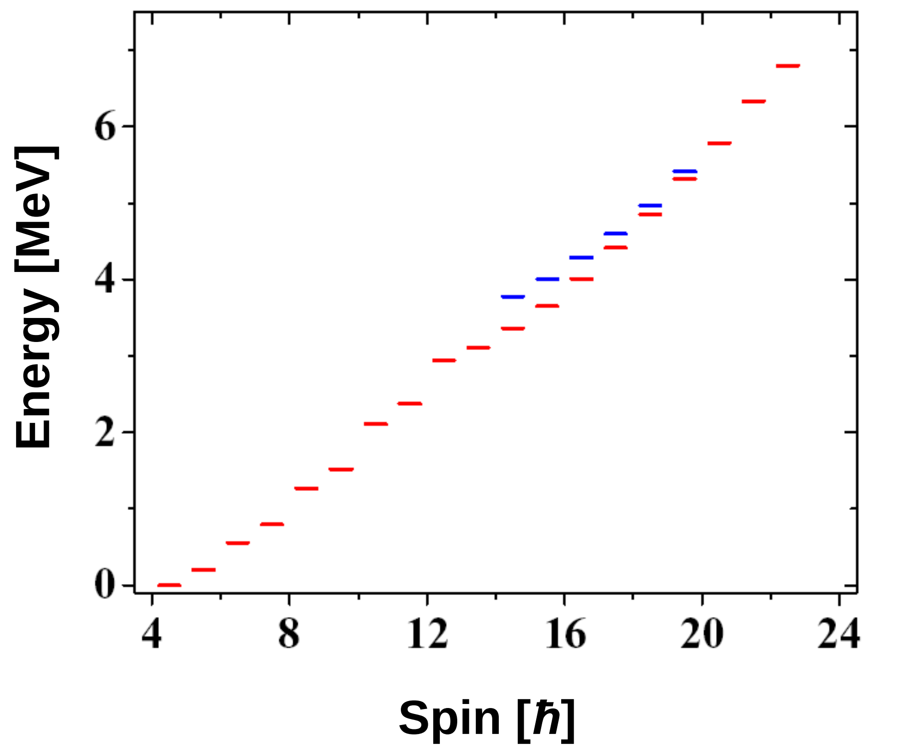


T. Ahn et al. to be published.

Doublet bands in odd-even ^{135}Nd near ^{134}Pr

S. Zhu et al., PRL 91(2003) 132501.

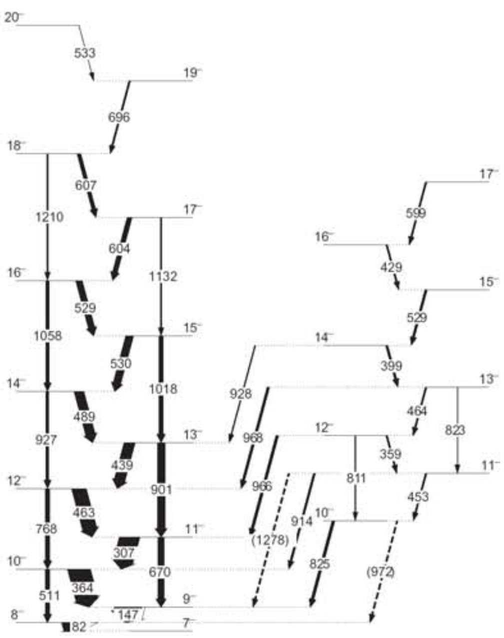




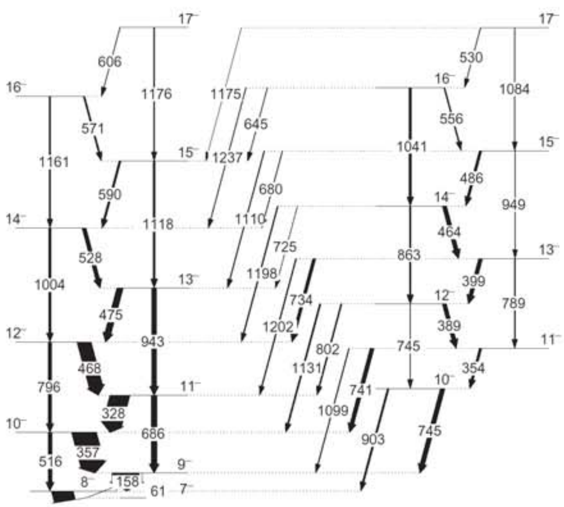
Systematics of odd-odd Rh isotopes near A~104

C. Vaman PRL92 (2004) 032501, P. Joshi et al., PLB in print.

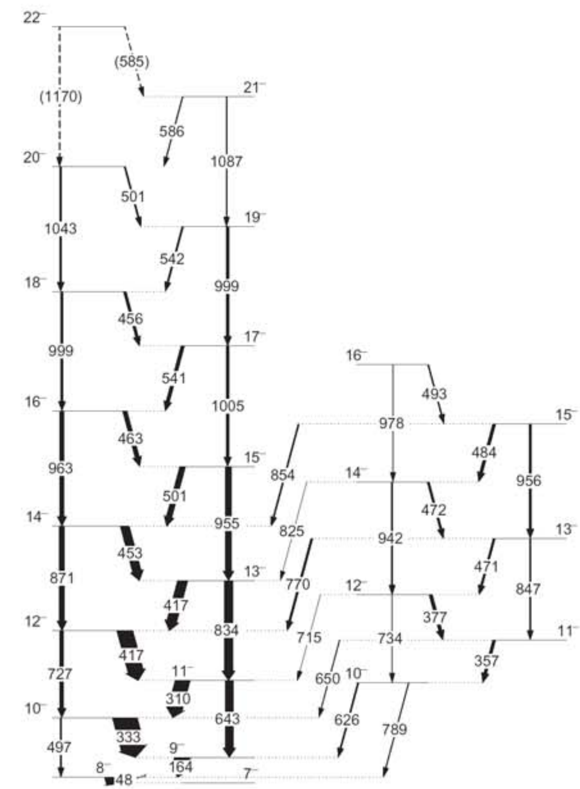
See posters of P.Joshi and C. Vaman



^{102}Rh



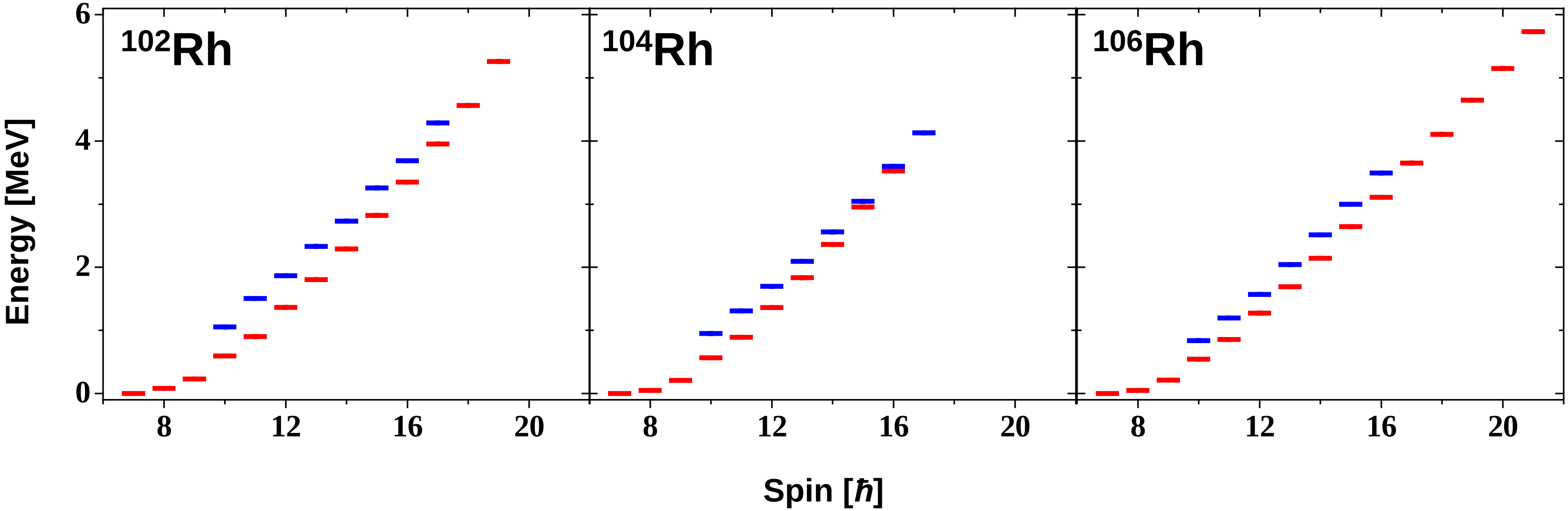
^{104}Rh



^{106}Rh

Systematics of odd-odd Rh isotopes near A~104

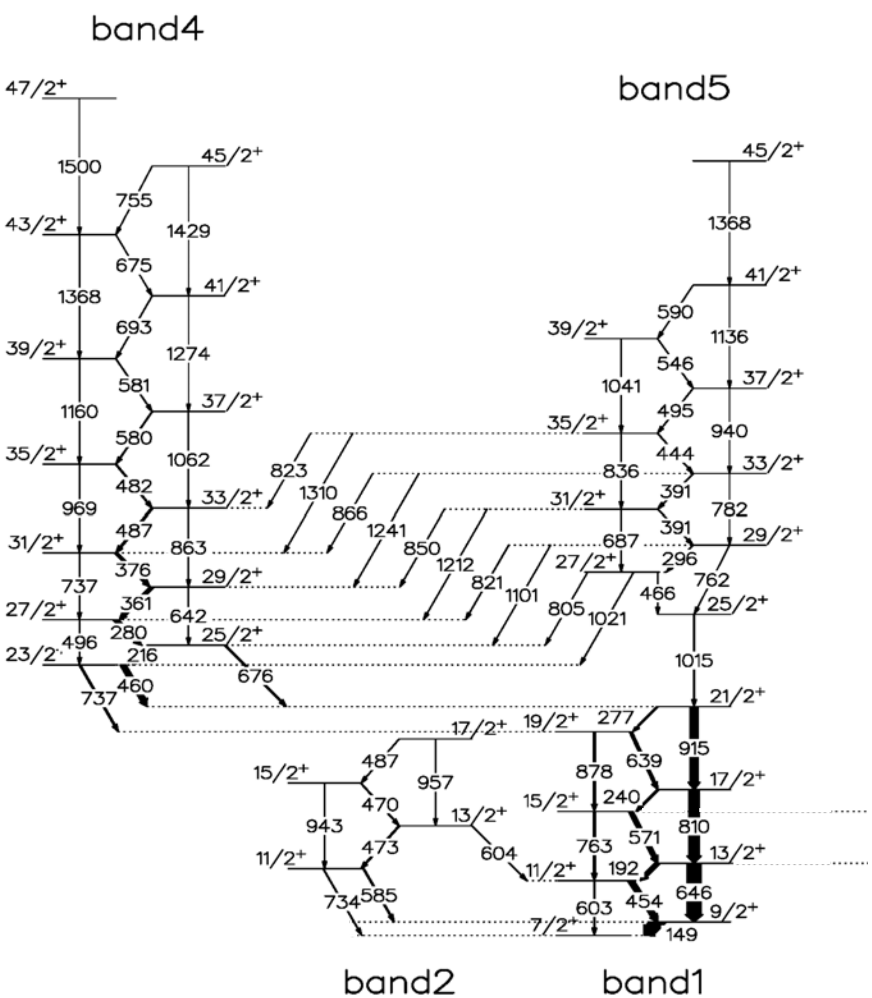
C. Vaman PRL92 (2004) 032501, P. Joshi et al., PLB in print.



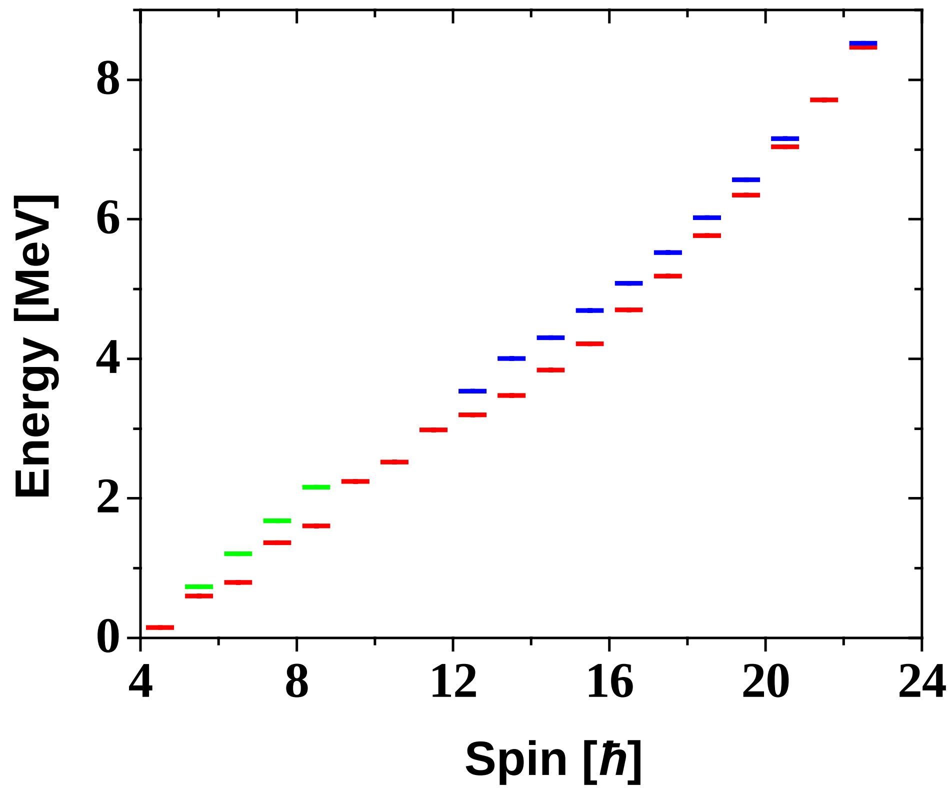
See posters of P.Joshi and C. Vaman

Doublet bands in ^{105}Rh

J. Timar et al., submitted to PLB.



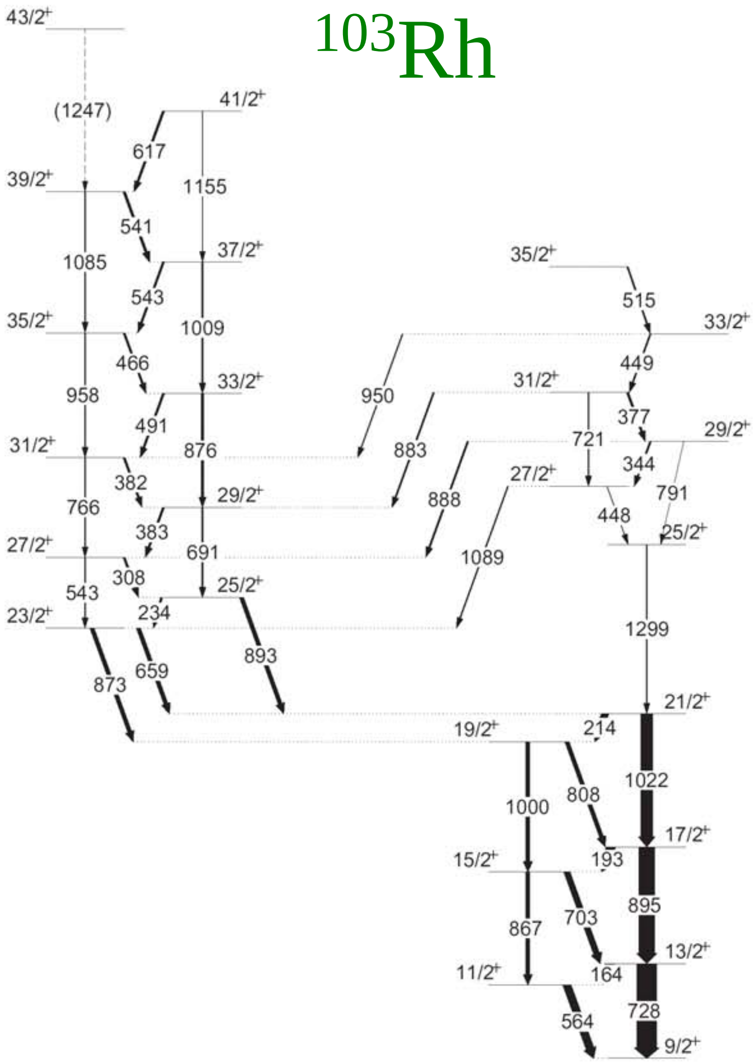
See the poster of J. Timar



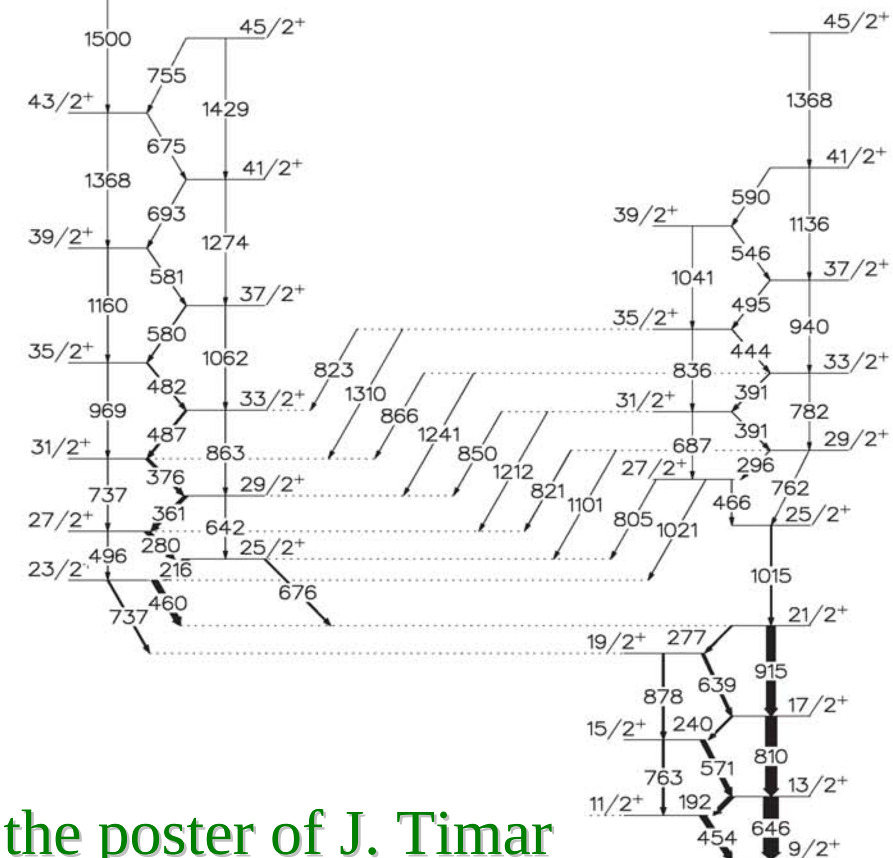
Doublet bands in odd-even ^{103}Rh and ^{105}Rh near ^{104}Rh

C. Vaman et al., J. Timar et al., submitted to PLB.

^{103}Rh

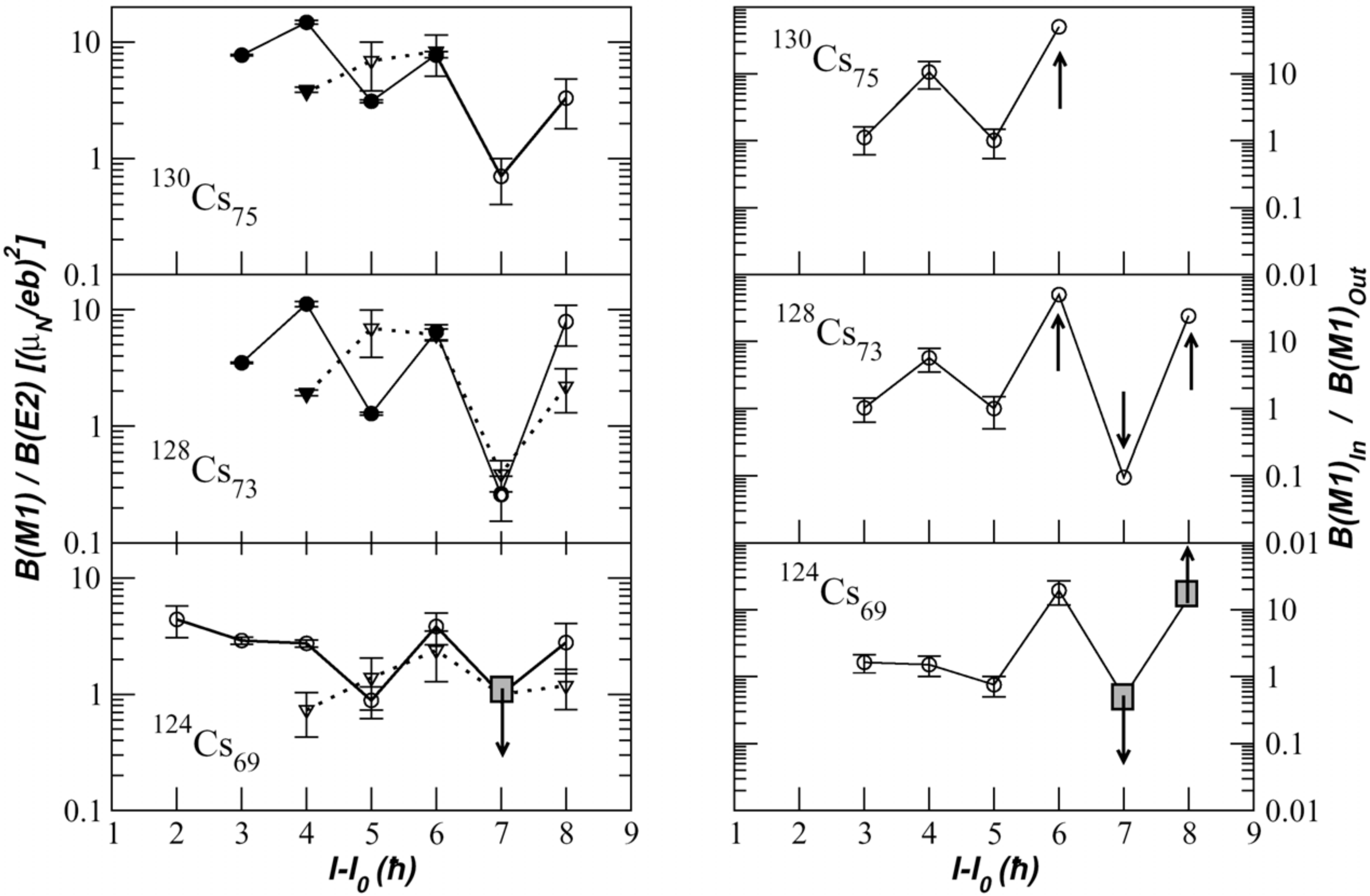


^{105}Rh

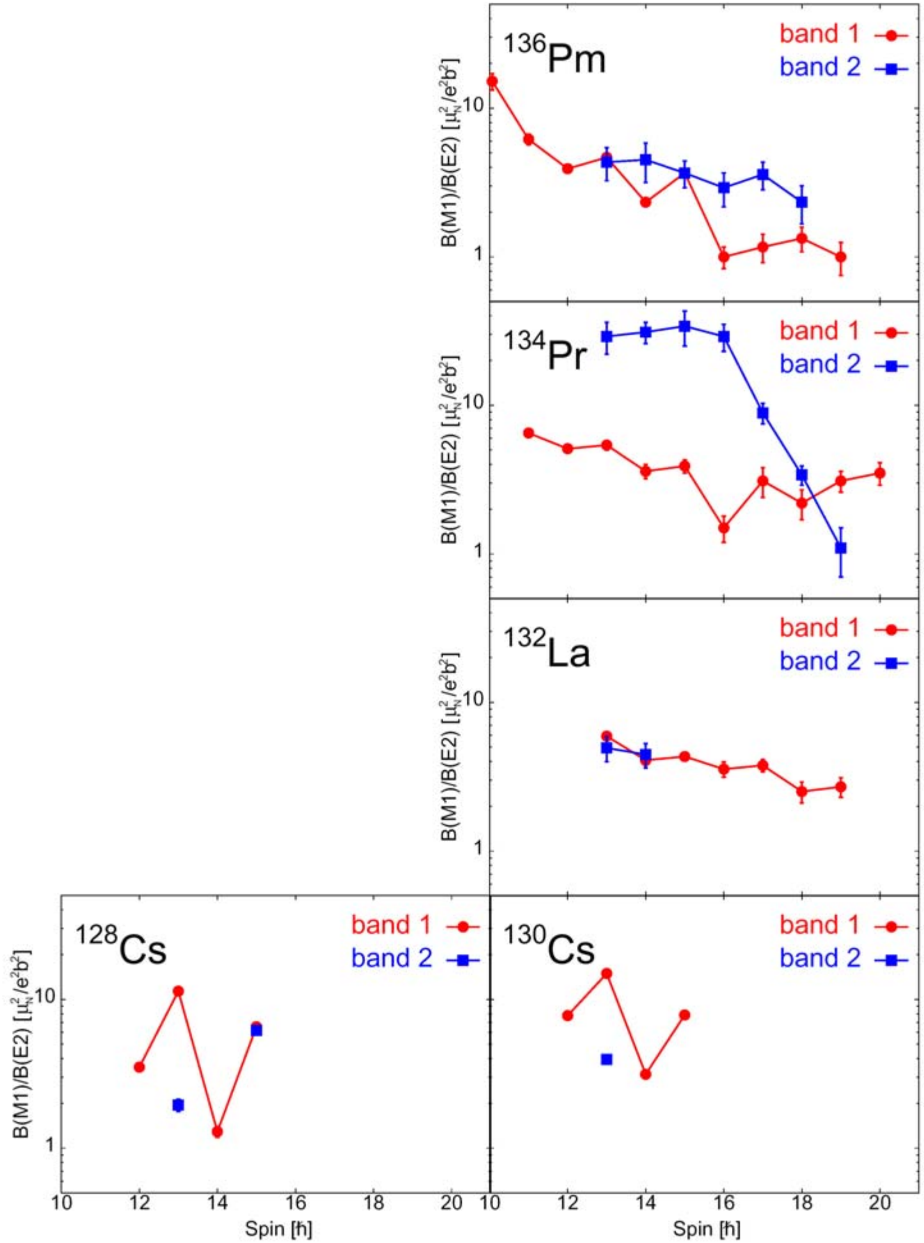


See the poster of J. Timar

Electromagnetic properties – pronounced staggering in experimental B(M1)/B(E2) and $B(M1)_{in}$ / $B(M1)_{out}$ ratios as a function of spin [*T.Koike et al. PRC 67 (2003) 044319].*



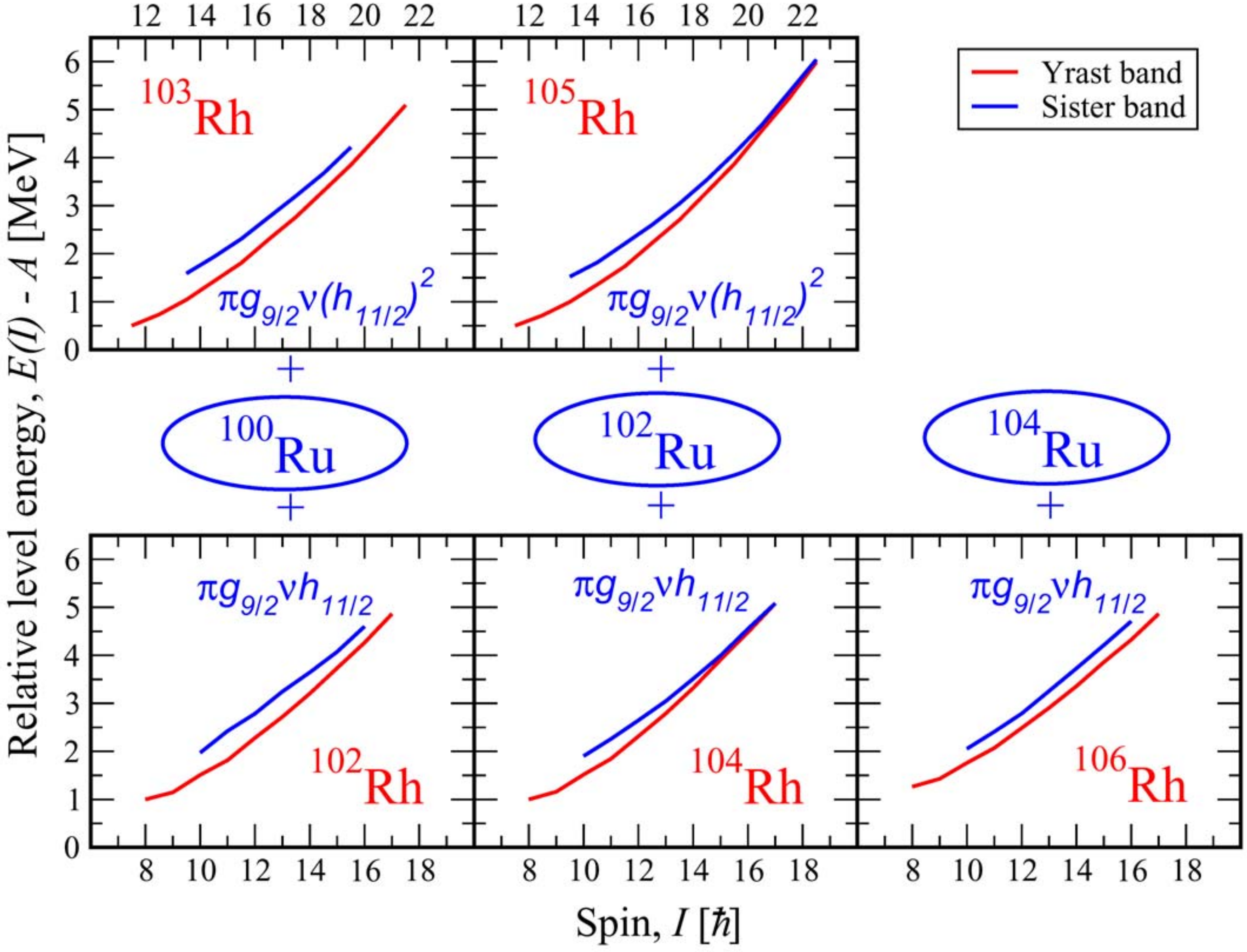
Electromagnetic properties – unexpected B(M1)/B(E2) behavior for ^{134}Pr and heavier N=75 isotones.



What have we learned from chirality so far?

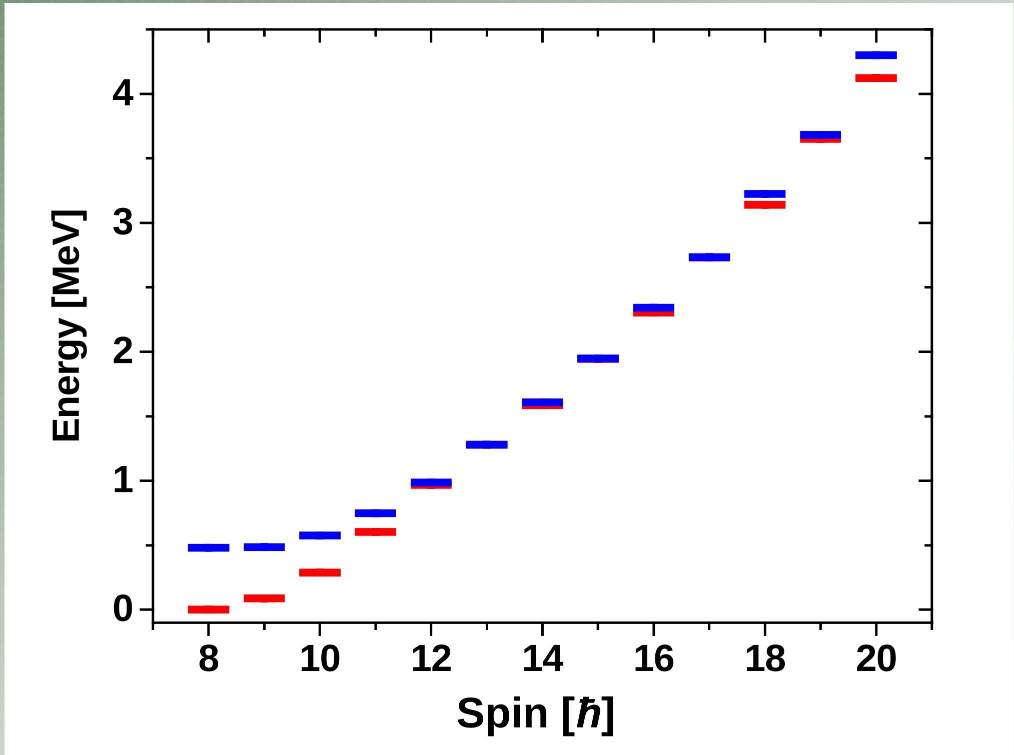
Chirality is a general phenomenon in triaxial nuclei:

- *two mass regions identified up to date,*
- *partner bands in odd-odd and odd-A nuclei.*



Energy separation vs. spin trend understood:

- *planar components at the low spin,*
- *degenerate levels at the medium spin,*
- *Coriolis alignment at the high spin.*

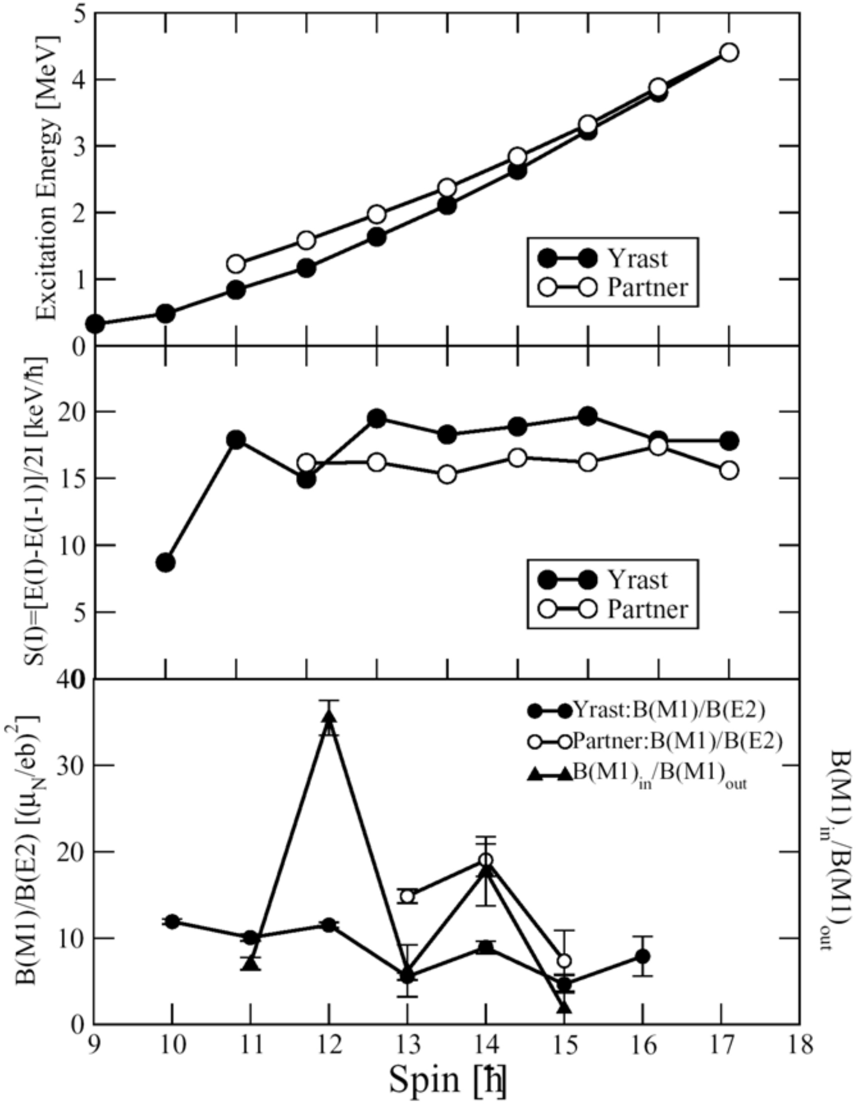


The smoking gun has been identified:

three fingerprints currently established for chirality in odd-odd triaxial nuclei:

- *near degenerate doublet $\Delta I=1$ bands for a range of spin I ;*
- $S(I)=[E(I)-E(I-1)]/2I$ *independent of spin* I;
- *chiral symmetry restoration selection rules for M1 and E2 transitions vs. spin resulting in staggering of the absolute and relative transition strengths.*

Based on the above fingerprints ^{104}Rh provides the best example of chiral bands observed up to date.



✓ *doubling of states*

✓ *S(I) independent of I*

✓ *B(M1), B(E2) staggering*

C. Vaman et al. PRL 92(2004)032501

A new limit of particle rotor model for triaxial nuclei has been identified:

For irrotational flow moment of inertia there are two special cases for which two out of three moments are equal:

axial symmetry

for $\gamma=0^o$ (prolate shapes)

$J_s=J_i=J_0 \quad J_l=0$

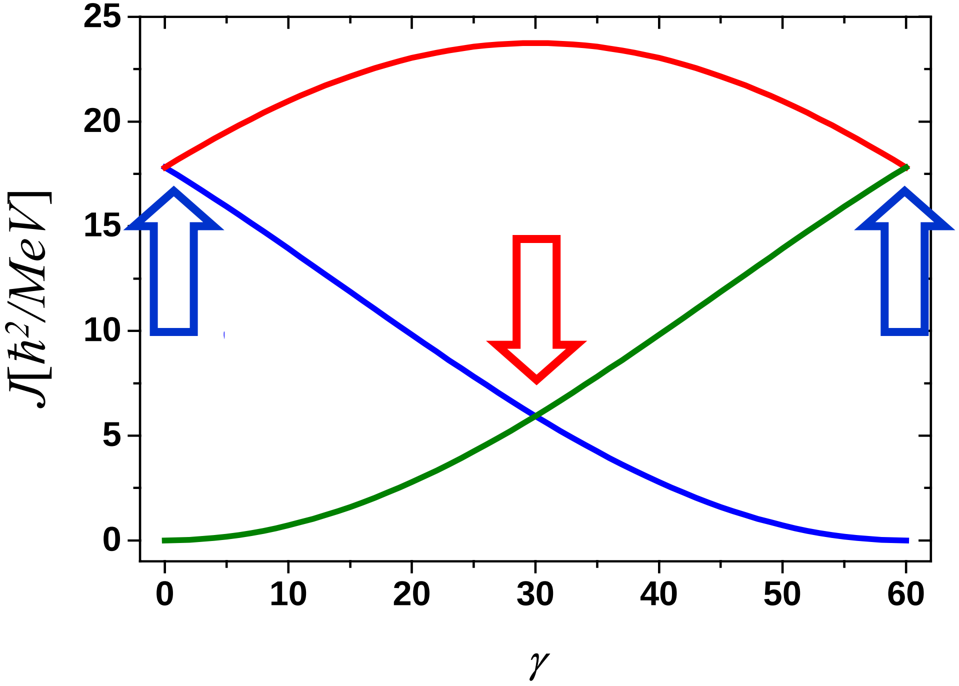
for $\gamma=60^o$ (oblate shapes)

$J_l=J_i=J_0 \quad J_s=0$

triaxiality

for $\gamma=30^o$ (triaxial shapes)

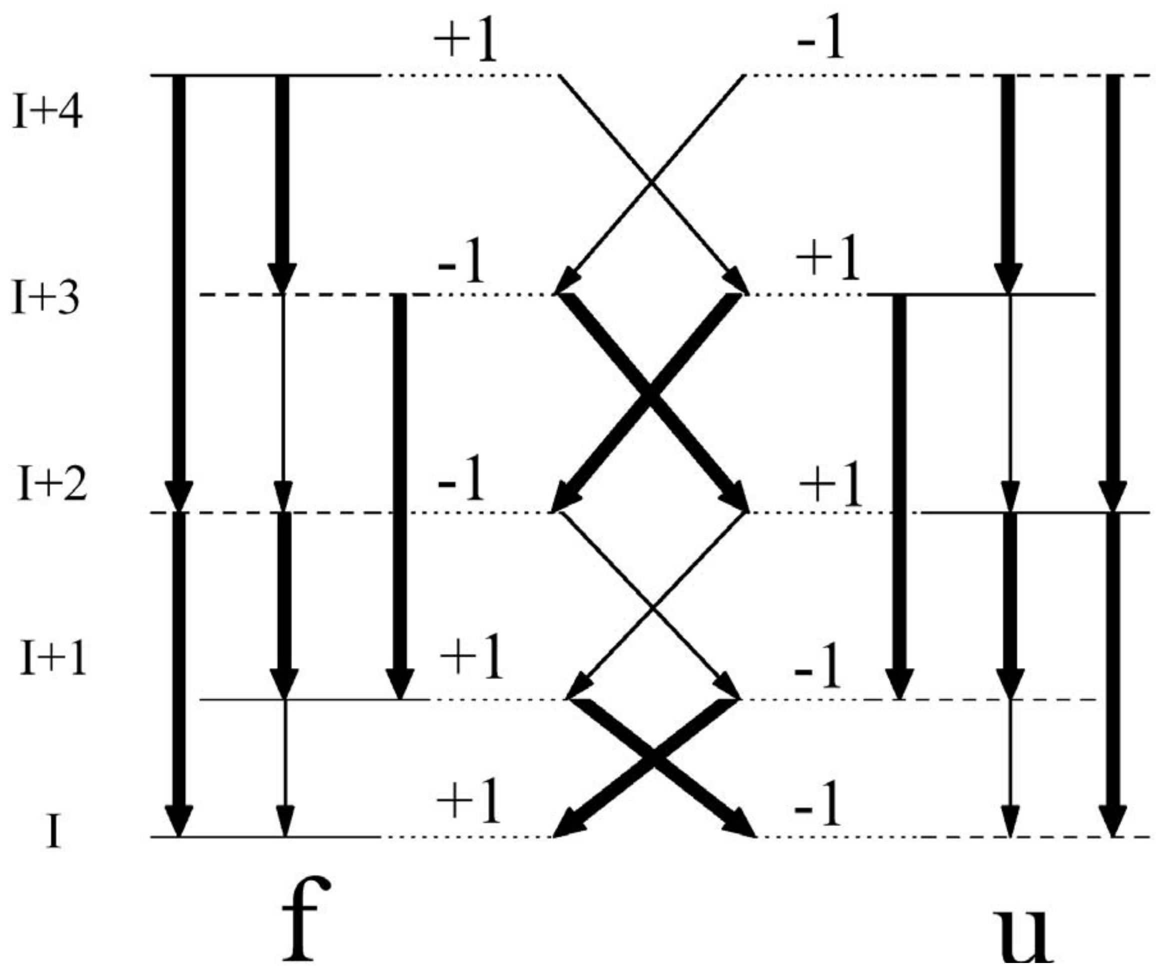
$J_l=J_s=J_0 \quad J_i=4J_0.$



For triaxial shapes at $\gamma=30^o$ the rotor hamiltonian has a very similar structure to the hamiltonian for axially symmetric shapes.

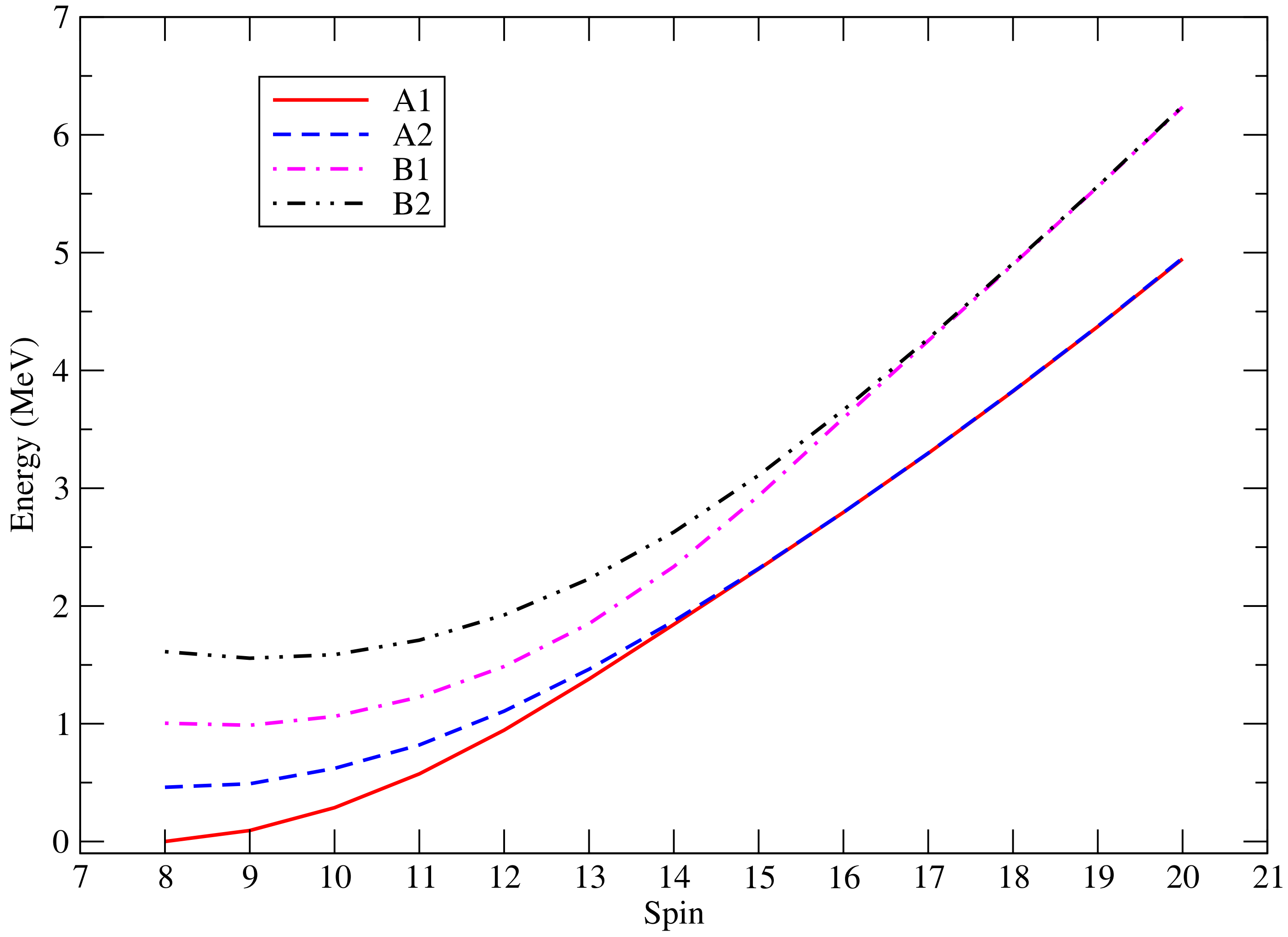
The intermediate axis becomes an effective symmetry axis.

New symmetry of particle rotor model for odd-odd chiral nuclei: results in selection rules and unique predictions for electromagnetic transition rates without a need for calculation.



T. Koike et al. , submitted to PRL

Conditions for chirality coincide with conditions for wobblers in the model Hamiltonian discussed in the next talk.



Chriality, open questions:

- *electromagnetic properties, transition rates,*
- *when the tunneling between the two handedness is appreciable and in which conditions the tunneling is expected,*
- *the criterion for the chiral bands: the degeneracy of doublet states as compared to rotational frequency.*